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Towards a Fast Reconstruction Paradigm for Urban Environments in Developing Regions Affected by Natural Disasters

Christopher Maestri
University of Arkansas, Fayetteville

Towards a Fast Reconstruction Paradigm for Urban Environments in Developing Regions Affected by Natural Disasters

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By

Christopher Maestri

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1) Introduction

Natural disasters in developing regions often displace people from their homes, into temporary shelters. These temporary shelters often consist of single-story pre-assembled tents designed to provide short-term aid for individual families [1]. Unfortunately, single-story temporary shelters are not sufficient for accommodating large displaced populations in urban settings due to issues of land overcrowding and disruption to utilities providing water sanitation and hygiene (WASH) services (along with many other issues).

The response to the 2010 Haiti earthquake demonstrates the need for a more efficient emergency shelter and reconstruction paradigm for urban environments. Following the magnitude 7.0 earthquake in Haiti, over 1.5 million people were displaced (as well as over 200,000 killed) [2]. Tent cities were quickly setup all over the capitol to provide immediate shelter as shown in Figure 1. With tents occupying available land, clean-up of rubble and eventual reconstruction were hindered, exacerbating poor conditions and prolonging the existence of these tent cities. Nearly five years after the initial disaster, approximately 85,000 Haitians were still displaced and living in “temporary shelters”, despite a total $13.5 billion in aid [3]. In the investigation by [3], the lack of efficiency and slow reconstruction progress were contributed to several factors: land right disputes, the use of foreign contractors, and overwhelming internal expenses within the various relief organizations providing the aid [3]. Reconstruction paradigms that facilitate the use of unskilled labor, allow for mountable and dismountable structures (overcoming land rights issues), and engage the locally affected manufacturing economy (rather than the economies of developed foreign countries) are desired.

Figure 1. Tent city at a refugee camp in Port-au-Prince, Haiti [4].

This study investigates the feasibility of implementing a multi-story steel structure, constructed with multi-use structural members and special end connectors, into future relief efforts. A multi-use structural member is an element whose original use is something other than being a structural member, but can be modified under certain circumstances, such as natural disasters, to create shelters for a displaced population. This allows for the member to be used initially in the shelter structure, and if the structure is no longer needed, it could be dismounted and the multi-use structural member could be used for its original purpose. A multi-story structure paradigm is needed to reduce congestion of available land (simply adding an additional story to a single-story shelter would reduce the required land area by half). Building upward instead of outward could also aid in the reconstruction and rubble removal process.

The paper starts by describing the search for a multi-use structural member within existing manufacturing supply chains in developing countries. Next, a description of the special end connection prototyping and experimental testing is provided. The results from the connection tests are then used in a multi-story structural system design and the construction of a prototype structure is discussed. Lastly, conclusions are made regarding the performance of the prototype structural components and design, along with a discussion on potential avenues for future work.

2) Identification of Multi-Use Structural Members

A multi-use structural member is an element whose original function could be easily modified to carry structural loads. The multi-use elements must be low-cost, lightweight, quickly and easily fabricated at an industrial scale, durable, and have good structural properties to allow construction of multiple stories. Example multi-use elements include light-gauge steel tubing from ventilation ducts, signposts, discarded drill-piping, roadway guardrails, drain gutters, etc. Ideally, the multi-use member could be produced at a large scale near the affected area so the displaced population receives the fastest response. Another trait of a multi-use member is that it can be re-used for its original purpose when the shelter is no longer needed.

In this study, the search for multi-use structural elements began on a global scale. Manufacturers located near developing regions and in disaster prone areas were investigated. The goal was to find a general type of element that was available in many locations. Many developing regions manufacture steel products, but steel ductwork was the only product investigated that met all the set requirements of a good multi-use structural member. Steel ductwork is produced worldwide, including South Africa, India, Malaysia, and even Puerto Rico, just 377 miles from Haiti [5]. Ductwork can also be found in many different shapes, but spiral (circular) ductwork was chosen for prototyping due to ease of manufacturing compared to square or rectangular geometries. Although round, spiral, ducts were chosen for this study, the connections developed could also be applicable to other hollow shapes.

3) Connection Prototyping

The goal when developing the connecting elements was to allow fabrication using sheet metal that could be folded into geometric shapes with structural properties, requiring no fasteners, power-tools, or skilled labor. Sheet metal was chosen to simplify shipping, reduce transport/storage volumes, and improve economy. The disallowance of fasteners requires the connections to resist forces through friction.

Small-scale prototypes were made to determine the best configuration for the connection. It was found that the connections performed best when inserted into each member instead of around the outside of the member. A connection that fits inside the member also allows for multiple members to be easily connected at one node, which is required in a multi-story structural system. Each individual piece of the connection also needed to be folded. This increases the moment of inertia of each piece, in turn increasing the stiffness. Folding each piece back on itself also doubles the area of friction that holds the pieces together as a complete connection. This increases pullout strength between elements.

Figure 2 shows the fabrication process for the prototype connector developed in this study. The final connection design consists of six individual sheet metal pieces with two 90° bends in the same direction spaced evenly about the centerline of each respective piece. These six pieces fit together using a series of properly spaced cuts in the metal. This design results in a simple connection that can combine five multi-use structural members at a single node. A small-scale version of the final design was fabricated prior to the creation of a full scale model.

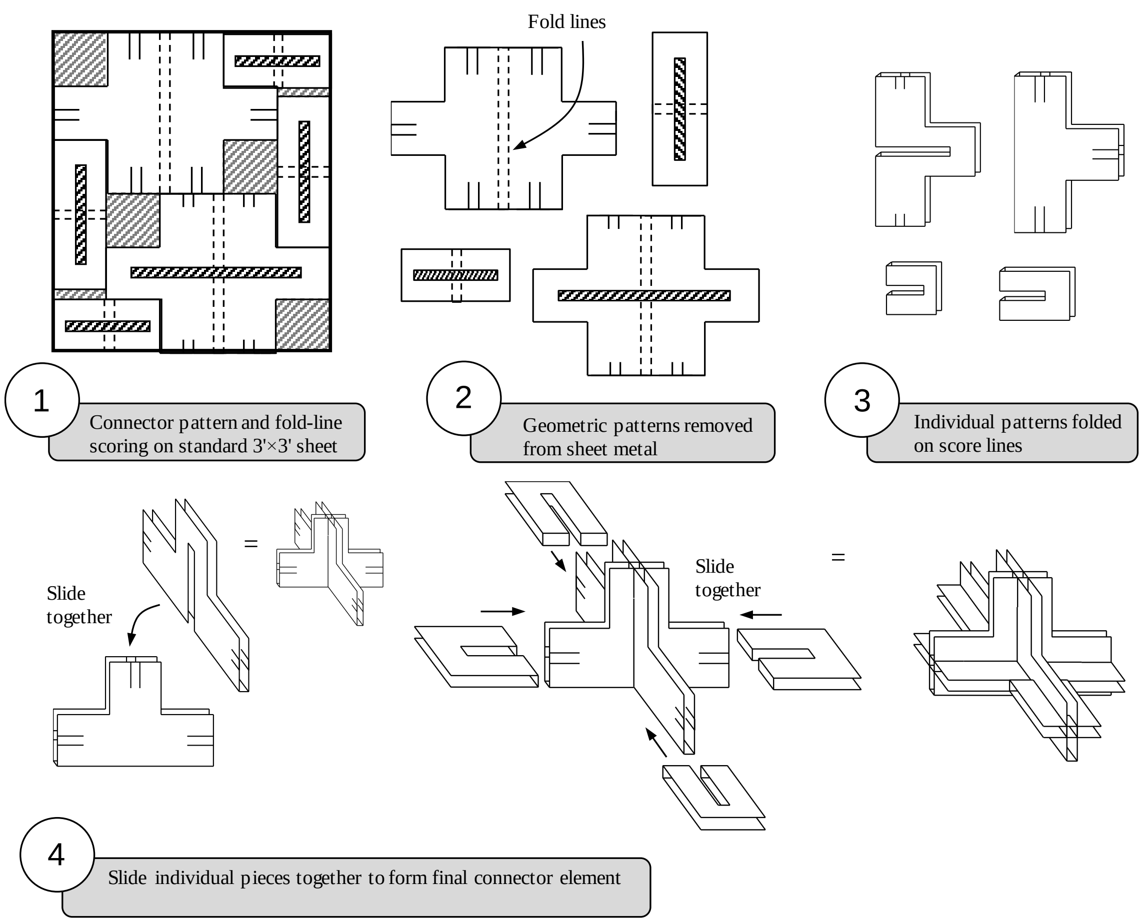

Figure 2. Connection fabrication process from flat sheet metal to final product.

4) Verification of Connection Capacity

To verify structural performance and aid in the design of the multi-story shelters, a full-scale prototype of the connection was created using the process described in Figure 2. Beam-column connection tests, as well as column buckling tests were conducted using the full-scale connection assembly and multi-use structural members.

The setup for the beam-column connection assembly included three sections of 8" diameter steel ventilation duct and one connection, as shown in Figure 3. The two duct sections representing the beams were identical at 31" long, and simply supported. The third duct section was shorter and placed on the top (vertical) arm of the connection representing the column. Note that circular wooden pieces (8" in diameter) were placed in the ends of the beams to prevent local buckling at the support reactions.

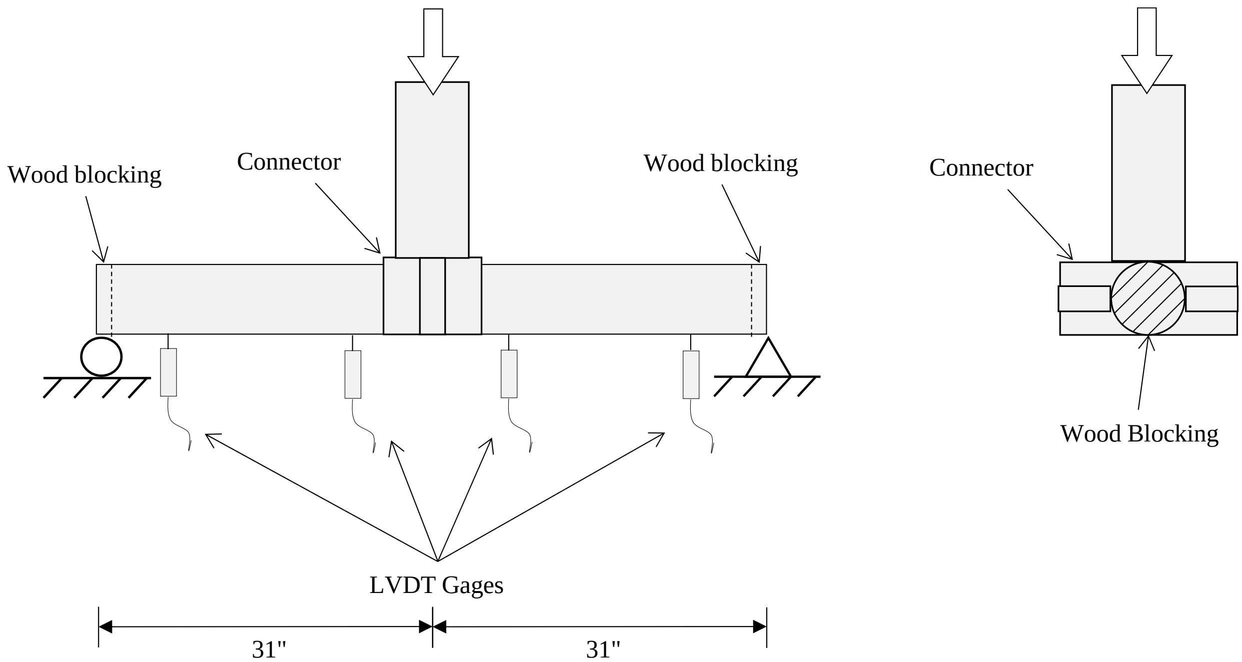

Figure 3. Testing configuration for beam-column connection assembly.

During testing, the applied load was measured through a load cell in the testing machine. Displacement was recorded along each beam length using four linear variable differential transducers (LVDTs) to allow beam rotation measurements. Figure 5 shows the measured moment versus rotation behavior for the connections. Moment, M, was calculated by multiplying the recorded applied load by the horizontal distance from one support to the column centerline (31"). The rotation, θ, was calculated by taking the inverse tangent of the recorded displacement divided by the horizontal distance from one support to the column centerline (31"). The maximum moment, M_{max}, was determined to be 1.987 kN-m (1466 lb-ft). Note that the maximum moment is controlled by the duct strength (local yielding of the duct cross-section) as the connection remained seemingly elastic. Duct damage near the connecting element is shown in Figure 4.

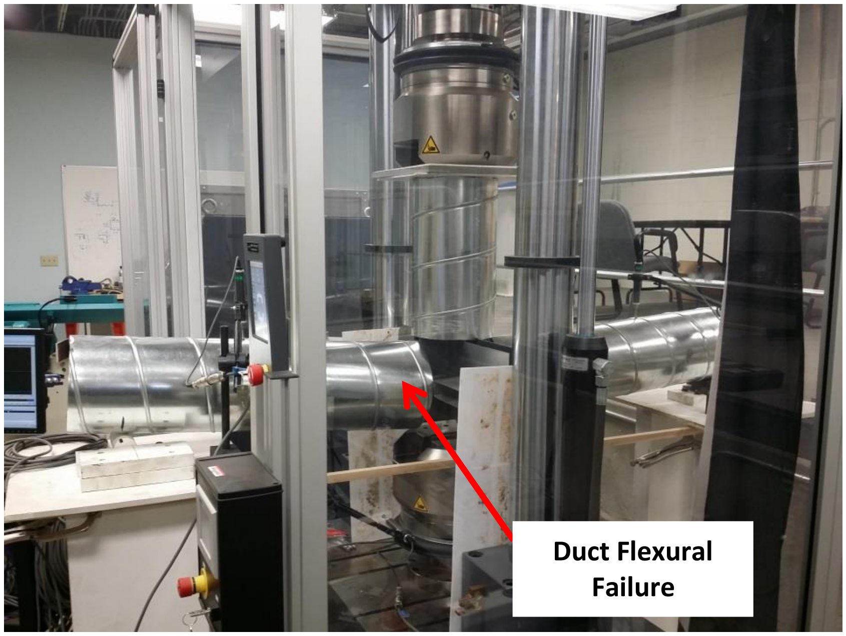

Figure 4. Duct flexural failure at connection.

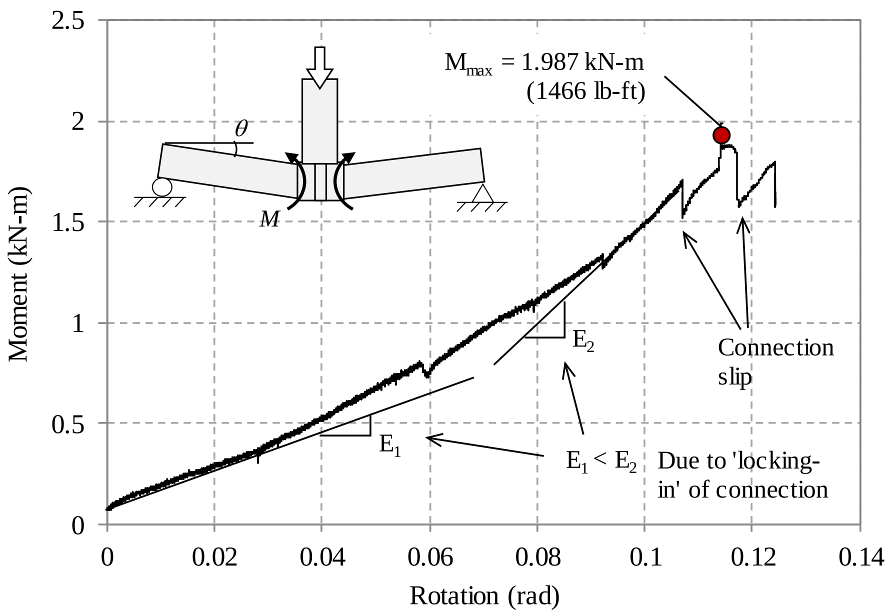

Figure 5. Moment versus rotation behavior for beam-column connection assembly.

Because the multi-use elements must function as columns, axial compressive strength must be understood prior to design. The setup for the column axial test consisted of a single 30" section of 8" diameter steel ventilation duct. This section was placed vertically in the loading machine as shown in Figure 6, and subjected to increasing axial loads until local buckling occurred (Figure 7). Figure 8 shows the load vs. time relationship during the column buckling test. The max axial load for the column was 15.06 kN (3386 lb). Global buckling was not observed, likely due to the limited size of specimen that could fit within the loading machine.

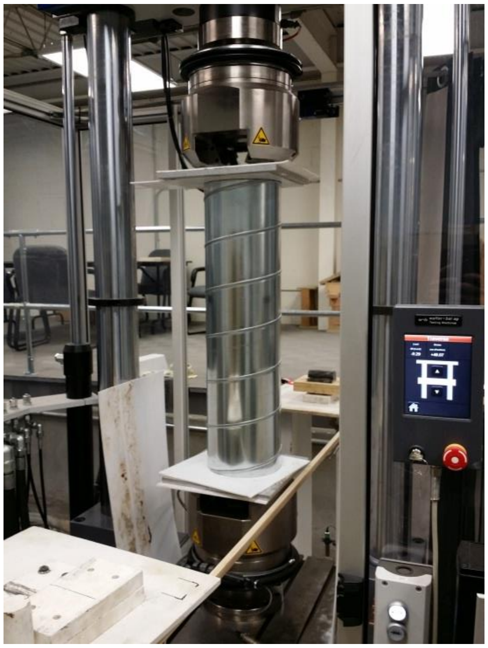

Figure 6. Column buckling test configuration.

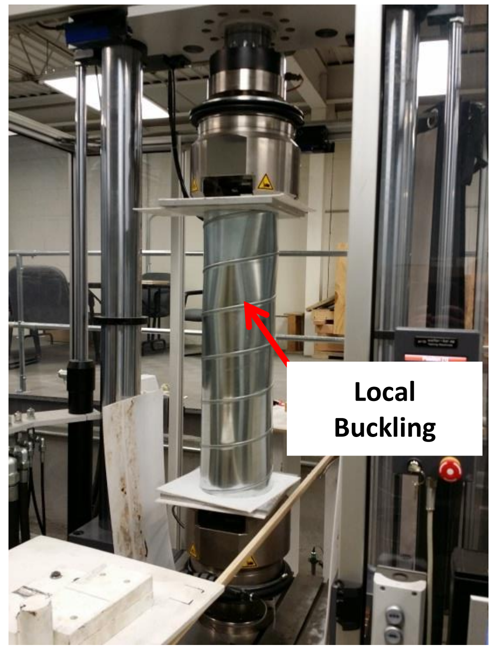

Figure 7. Local buckling failure.

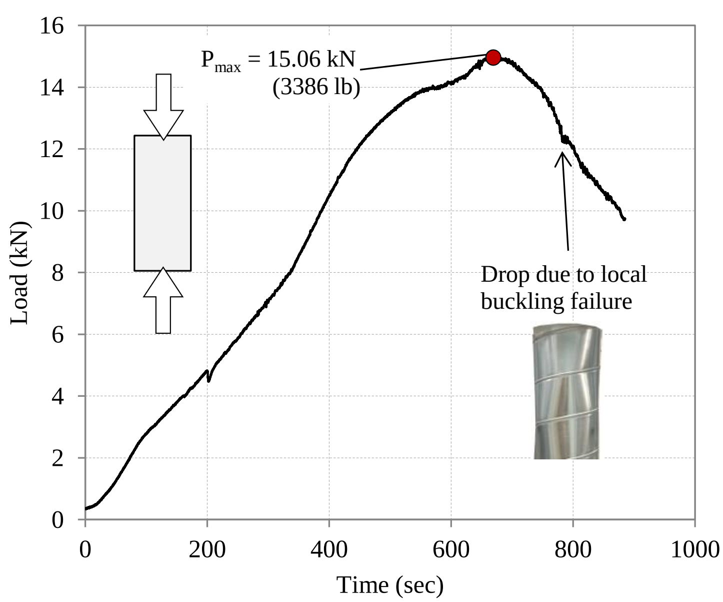

Figure 8. Load versus time behavior for the column.

5) Structural System Design and Prototype Structure

Understanding the beam-column flexural capacities and axial column capacities allows for proportioning of the multi-story structural system. In this study, a two-story structural design was considered. Assuming local buckling controlled the axial strength of the columns, a story height of 8 ft was chosen for the columns to allow for adequate headroom. The beam span length was determined through an analysis of connection flexural demands within a rectangular plane frame having an arbitrary beam length of L (Figure 9). The stiffness method of analysis exploiting symmetry (with two degrees of freedom, θ_B and θ_C) was chosen, and is described in the following paragraphs.

To proportion the beam lengths such that adequate capacity is provided, the peak moment demand from the analysis (derived in terms of L) is set equal to the measured moment capacity determined from the beam-column testing. The complete calculation is shown below, assuming a design dead load of 5 lb/ft^2 and a live load of 25 lb/ft^2.

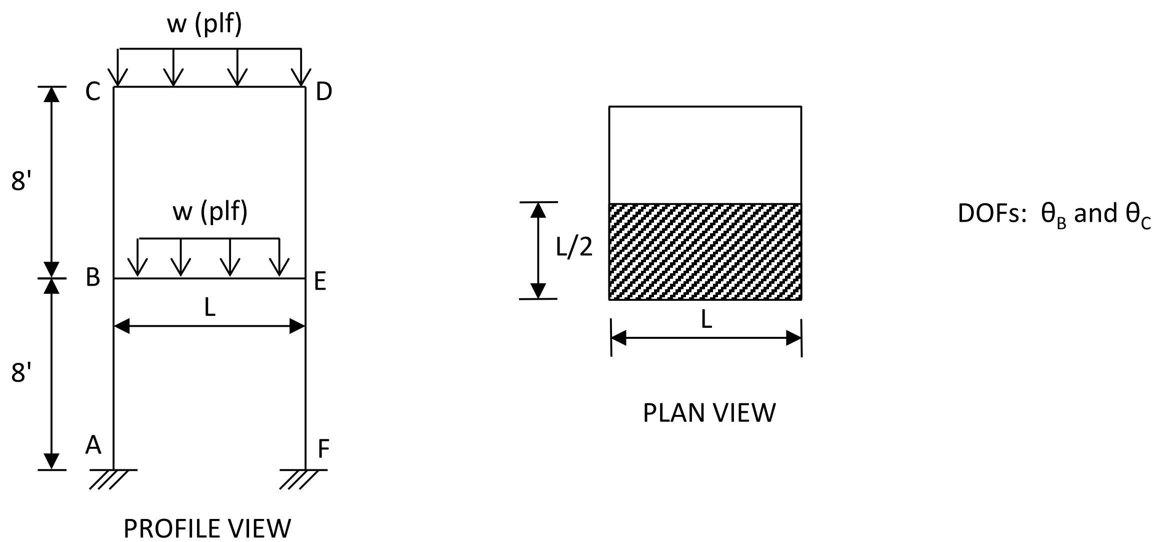

Figure 9. Prototype two-story structure design parameters.

$$Factored\ Load = 1.2DL + 1.6LL = 1.2(5\ psf) + 1.6\ (25\ psf) = 46\ psf$$

$$w = Factored\ Load * Trib.Width = 46\ psf * \frac{L}{2}\ ft = 23L\ plf$$

To begin analyzing the structure using the stiffness method, reactions due to applied loading were calculated. Next, reactions due to a unit rotation at B (θ_B) from the above structural configuration were calculated. Finally, reactions due to a unit rotation at C (θ_C) were calculated. All reactions are shown in Figure 10.

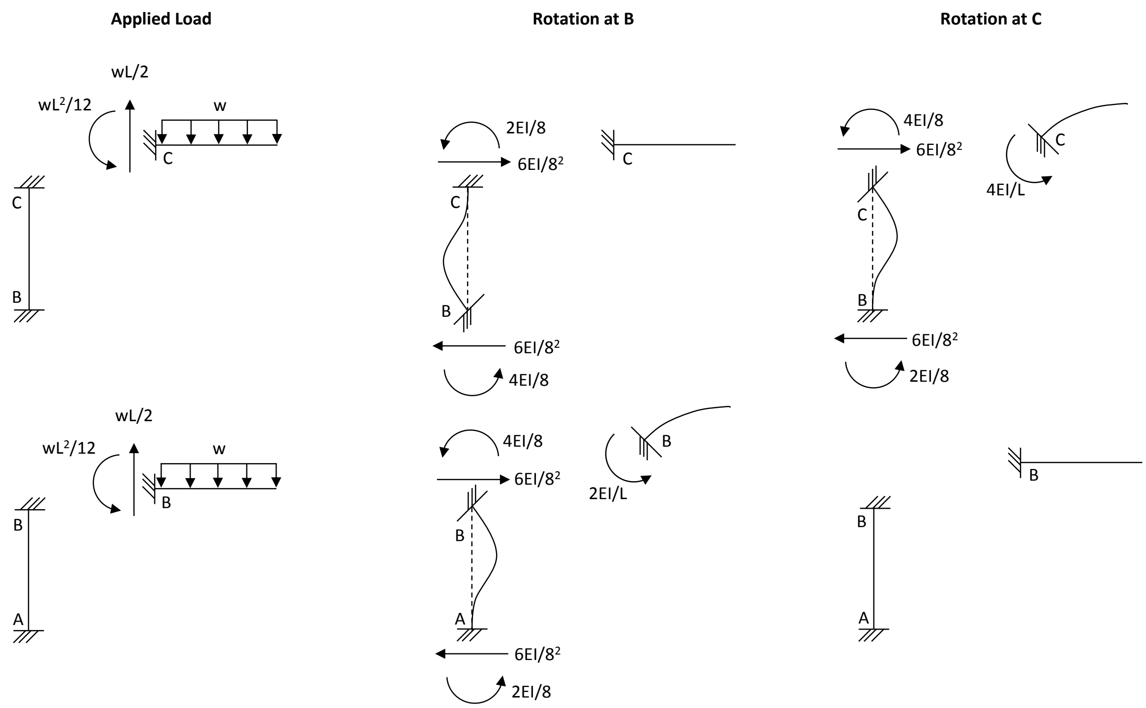

Figure 10. End moment and shear reactions calculated using the stiffness method.

Equilibrium equations formulated through superposition (shown below) are used to solve for the actual joint rotations, θ_B and θ_C:

1. $$\frac{wL^2}{12} + \left(\frac{4EI}{8} + \frac{4EI}{8} + \frac{2EI}{L}\right)\theta_B + \left(\frac{2EI}{8}\right)\theta_C = 0$$

1. $$\frac{wL^2}{12} + EI\left(1 + \frac{2}{L}\right)\theta_B + (0.25EI)\theta_C = 0$$

2. $$\frac{wL^2}{12} + \left(\frac{2EI}{8}\right)\theta_B + \left(\frac{4EI}{8} + \frac{2EI}{L}\right)\theta_C = 0$$

2. $$\frac{wL^2}{12} + (0.25EI)\theta_B + EI\left(0.5 + \frac{2}{L}\right)\theta_C = 0$$

In matrix form, the above equations can be represented as:

$$\begin{pmatrix} \dfrac{wL^2}{12} \\ \dfrac{wL^2}{12} \end{pmatrix} + EI\begin{pmatrix} 1 + \dfrac{2}{L} & 0.25 \\ 0.25 & 0.5 + \dfrac{2}{L} \end{pmatrix}\begin{pmatrix} \theta_B \\ \theta_C \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Solving for θ_B and θ_C gives:

$$\begin{pmatrix}\theta_B \\ \theta_C\end{pmatrix} = \begin{pmatrix} 0.25(\frac{wL^2}{12}) - \frac{wL^2}{12}(0.5 + \frac{2}{L}) \\ 0.25(\frac{wL^2}{12}) - \frac{wL^2}{12}(1 + \frac{2}{L}) \end{pmatrix} \frac{1}{(\frac{4}{L^2} + \frac{3}{L} + 0.4375)EI}$$

The critical end moments (Beam BE and CF) were set less than or equal to M_{max} = 1466 lb-ft and L was solved:

<u>Beam BE End Moment (w = 23L plf)</u>

$$\frac{wL^2}{12} + \frac{2EI}{L}\theta_B \le (M_{max} = 1466\ lb * ft)$$

$$\frac{wL^2}{12} + \frac{2EI}{L}\left(\frac{0.25\left(\frac{wL^2}{12}\right) - \frac{wL^2}{12}\left(0.5 + \frac{2}{L}\right)}{\left(\frac{4}{L^2} + \frac{3}{L} + 0.4375\right)EI}\right) \le 1466\ lb * ft$$

$$1.917L^3 + \frac{2}{L}\left(\frac{0.4792L^3 - 1.917L^3\left(0.5 + \frac{2}{L}\right)}{\left(\frac{4}{L^2} + \frac{3}{L} + 0.4375\right)}\right) \le 1466\ lb * ft$$

$$L \le 9.61\ ft$$

<u>Beam CF End Moment (w = 23L plf)</u>

$$\frac{wL^2}{12} + \frac{2EI}{L}\theta_C \le (M_{max} = 1466\ lb * ft)$$

$$\frac{wL^2}{12} + \frac{2EI}{L}\left(\frac{0.25\left(\frac{wL^2}{12}\right) - \frac{wL^2}{12}\left(1 + \frac{2}{L}\right)}{\left(\frac{4}{L^2} + \frac{3}{L} + 0.4375\right)EI}\right) \le 1466\ lb * ft$$

$$1.917L^3 + \frac{2}{L}\left(\frac{0.4792L^3 - 1.917L^3\left(1 + \frac{2}{L}\right)}{\left(\frac{4}{L^2} + \frac{3}{L} + 0.4375\right)}\right) \le 1466\ lb * ft$$

$$L \le 10.19\ ft$$

As shown in the above calculations, the maximum allowable span length for the beams is 9.61 ft. To simplify the design, a beam span length of 8 ft was chosen so that beams and columns would not be confused during construction.

Due to time and material availability, a two-story plane-frame was constructed instead of a complete two-story structure. The columns and beams in the plane-frame were all 5 ft in length (the available size at the time); however plans are underway to construct the full-scale prototype 2-story structure. The prototype construction required the fabrication of three more connections identical to the one used in testing. The plane-frame construction was completed by a single person in approximately 25 minutes. Given this, it is estimated that the construction of a complete two-story frame would take approximately 1 hour and 15 minutes with the same single-person workforce. These values do not include time spent constructing the connections. The prototype plane-frame is shown in Figure 11, lying horizontally on the ground.

Figure 11. Two-story plane frame prototype structure with 5' members.

6) Conclusions

This study investigated a fast reconstruction paradigm for urban environments affected by natural disasters. It analyzed the feasibility of implementing a multi-story steel structure, constructed with multi-use structural members and special end connectors, into future relief efforts. The analysis included the determination of a multi-use structural member, special end connection prototyping, connection assembly and axial column testing, and structural system design. The following conclusions are based on the results from the connection development, structural testing, and prototype system design:

1. A structural connection can be fabricated from folded sections and provide sufficient strength for carrying realistic shelter loads in a multi-story structural system. Beam-column assembly tests determined the maximum moment capacity for the connection to be 1.987 kN-m (1466 lb-ft). This capacity was controlled by the strength of the 8" spiral ventilation ducts, allowing higher loads or longer beam spans with the use of lower gauge metal ducts.

2. Column compressive testing demonstrated a maximum axial load for the 8" spiral ventilation duct at 15.06 kN (3386 lb), limited by local buckling of the tube wall.

3. Using the stiffness method of analysis, and the element and connection capacities determined through testing, 8 ft duct elements could support a 5psf dead load and 25psf live load. These loads with this structural geometry equate to approximately 9 people weighing 175 lb each, per shelter room.

4. Construction of a prototype two-story plane-frame was completed in 25 minutes with one laborer; therefore, construction of a complete two-story frame would take approximately 1 hour and 15 minutes. These values do not include time spent constructing the connections.

5. Lateral load tests need to be conducted, to ensure adequate performance of the two-story system in seismic and wind loading.

7) References

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